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Evidence of direct T violation in the B system

Ezequiel Álvarez [(a)1] and Alejandro Szynkman [(b)2]

a: *Departamento de Física Juan José Giambiagi,*
Facultad de Ciencias Exactas y Naturales,
Universidad de Buenos Aires, Ciudad Universitaria,
Pabellón 1, 1428, Buenos Aires, Argentina

b: *Physique des Particules, Université de Montréal,*
C.P. 6128, succ. centre-ville, Montréal, QC, Canada H3C 3J7

Abstract

In this letter we reinterpret and reanalyze the available data of the B-factories showing the existence of experimental evidence of direct T violation in the B system. This reinterpretation consists in using the available observables to define a new observable which, in a model independent way and without assuming CPT invariance, compares a transition between a flavour B-state and a here-defined B_α-state, and its T-reversed transition. This new observable turns out to be, in addition, not null in the limit of a vanishing mean life time difference between the neutral B mass eigenstates. As far as the authors are concerned, this is the first existing evidence of direct T violation in the B system.

[1] sequi@df.uba.ar

[2] szynkman@lps.umontreal.ca

1 Introduction

In the last fifty years there has been a great theoretical and experimental advance in the study of the discrete symmetries C (charge conjugation), P (parity), T (time reversal) and their relevant combinations CP, T and CPT. This was achieved thanks to the exploration of the Electroweak sector of the Standard Model where, at the level of energies explored insofar, we understand that the root of CP and T violation lies. On the other hand, CPT symmetry is protected by the general Pauli's CPT theorem [1] and it has not been measured to be violated.

During this period we have learned that the study of the discrete symmetries may give us clues to project the behaviour of physics at higher energies. As it is the case of the celebrated prediction of the third generation [2] in answer to the CP violation measured in the Kaon system [3]. It is therefore of great interest the study of the discrete symmetries in the different sectors of the Electroweak Lagrangian.

The violation of CP has been deeply and extensively studied in the Kaon system since its first measurement in 1964. The following experimental and theoretical studies, in the 70's and 80's, pointed out that an important CP violation should be expected in the B sector. In fact, this was measured for the first time by Babar and Belle in 2001 [4], and since then an amazing amount of data and a very high accuracy in the measurements have considerably increased our knowledge of the Electroweak sector.

On the contrary, there is poor knowledge of T violation, which was not directly measured until 1998 by the CPLEAR collaboration [5]. This measurement was performed in the Kaon system and, up to now, it is the only direct measurement for T violation that exists. We mention, though, that this T-violating observable has been subject of controversy [6, 7] due to its dependence on the Kaons mean life time difference. The search for a similar T-violating observable in the B-sector by the B-factories, which compares the $\Gamma(B^0 \to \bar{B}^0, \Delta t)$ and $\Gamma(\bar{B}^0 \to B^0, \Delta t)$ transitions, it has thrown negative results [8], as expected due to the negligible mean life time difference ($\Delta\Gamma$) in the neutral B mesons. As a matter of fact, time reversal invariance is also proposed to be explored in the B system through T-odd observables [9] which show up through the angular analysis of certain B decays.

It may seem quite puzzling, given the close relationship that exists between CP and T due to the CPT theorem, that CP violation has been so well explored in the B system, whereas signals for T violation have not been observed in this sector yet. This is the problem that we address in this letter, and we face it as follows: (i) we show how a proposed T-violating observable for the B-factories measures, in a model independent way and without assuming CPT invariance, direct T violation in a transition between some given neutral B-states; (ii) we show, within the Standard Model (SM), that this observable is different from zero even in the limit $\Delta\Gamma \to 0$, and that this T violation is the expected one from the CP violation measured in the interference of decays with and without mixing in $B \to J/\psi K_{S,L}$ due to the CPT theorem; and (*iii*) we reanalyze the available experimental data and compute this T-asymmetry to positively find direct T violation in the B system.

The observable that we propose has been previously studied within different contexts and theoretical assumptions [10, 11]. In this letter, however, besides presenting it as a direct comparison between a transition and its T-reversed in a model independent way and beyond any theoretical assumption, we also compute its value using the available data.

This work is organized as follows: in Section 2, we define the T-violating observable and we show, using experimental information and quantum mechanics, that this observable corresponds to an asymmetry between a given process and its T-reversed; in Section 3, we interpret and study the observable within the SM and we predict its value to be proportional to $\sin(2\beta)$; in Section 4, we compute the observable using the experimental data of Babar and Belle and we present evidence of direct T violation in the B system; Section 5 contains the conclusions and final remarks.

2 A model independent direct T-violating observable for the B-factories

In this Section we propose and discuss a suitable observable for the B-factories, Babar and Belle, which measures direct T violation in a model independent way.

The T-operation, in contrast with the CP-operation, corresponds to an anti-unitary operator and hence it has no conserved quantum numbers. Therefore, we cannot assert that T is either conserved or not in a given process or decay; instead we should say that the process is *T-invariant* or not. Hence, the only way to inquire directly about the T-invariance of a given process is by comparing it with its T-reversed. For instance, if ϕ_1 and ϕ_2 are two possible quantum states, then the inequality

$$|\langle\phi_2|U(\Delta t)|\phi_1\rangle|^2 \neq |\langle\phi_1|U(\Delta t)|\phi_2\rangle|^2, \tag{1}$$

where $U(\Delta t)$ stands for the evolution operator, is a clear signal that the process is not T-invariant (usually referred as *T violation*, for short). A direct measurement of an equality of this type is an explicit measurement of direct T violation, as it was the case of CPLEAR in the Kaon system [5]. In this Section, we show that in the B-factories it is possible to construct an asymmetry which confirms an inequality of the type in Eq. (1), and hence direct T violation in the B system. Moreover, since $\Delta\Gamma$ is negligible in the B system, this asymmetry is free of any argument that might arise due to a considerable mean life time difference [6].

For the purposes of this paper, we consider the events in the B-factories in which the $\Upsilon(4S)$ decays to a pair of correlated neutral B mesons. Once this correlated pair is created, the first decay of one of these mesons tags the other meson, which evolves during a Δt time until it decays. The process of *tagging* in a correlated couple of particles occurs always no matter which is the first decay. In the B-factories, where the correlated initial state at time t is written as

$$|i(t)\rangle \;=\; \frac{e^{-\Gamma t}}{\sqrt{2}}\left(|B^0(+\vec{k}),\bar{B}^0(-\vec{k})\rangle - |\bar{B}^0(+\vec{k}),B^0(-\vec{k})\rangle\right), \tag{2}$$

a first decay to X at time t_1 projects the second meson still flying to

$$e^{-\Gamma t_1}|B_{\bar{X}}\rangle \equiv e^{-\Gamma t_1}\frac{1}{\sqrt{2}}(\langle X|T|B^0\rangle|\bar{B}^0\rangle - \langle X|T|\bar{B}^0\rangle|B^0\rangle), \tag{3}$$

where Γ^{-1} is the mean life time of the B mesons and T is the 'scattering' matrix of the direct decay –with no mixing. Hence, we say that the first decay has acted as a filter in the quantum mechanical sense and has tagged the second meson as a $|B_{\bar{X}}\rangle$. The state of the second meson is as physical and determined as it is –for instance– a flavor state B^0, even if the $B\to X$ decay is not theoretically well understood. Therefore, every time that we have an X decay on one side we know that a $B_{\bar{X}}$ must occur on the other side, and this conclusion is achieved beyond any theoretical assumption.

Suppose that the first decay of the correlated B pair is $B\to X = J/\psi K_S$, then the tagged meson is

$$|B_{\overline{J/\psi K_S}}\rangle \;=\; \frac{1}{\sqrt{2}}(\langle K_S|T|B^0\rangle|\bar{B}^0\rangle - \langle K_S|T|\bar{B}^0\rangle|B^0\rangle). \tag{4}$$

This motivates us to define a new orthonormal basis in the B-space such that one of its vectors is parallel to $B_{\overline{J/\psi K_S}}$,

$$|B_\alpha\rangle \;=\; \frac{1}{\sqrt{N}}(\langle K_S|T|B^0\rangle|\bar{B}^0\rangle - \langle K_S|T|\bar{B}^0\rangle|B^0\rangle) \tag{5}$$

$$|B_{\alpha_\perp}\rangle \;=\; \frac{1}{\sqrt{N}}\left((\langle K_S|T|\bar{B}^0\rangle)^*\,|\bar{B}^0\rangle + (\langle K_S|T|B^0\rangle)^*\,|B^0\rangle\right), \tag{6}$$

where N is the normalization factor. These two new states are well and unambiguously defined through these equations, and hence they are physical. It is worth noticing at this point that due to Bose-statistics we can assert a first important feature of this basis, namely the impossibility of B_α to decay directly to $J/\psi K_S$:

$$\langle K_S|T|B_\alpha\rangle \;=\; 0. \tag{7}$$

Using this new basis, we can rewrite the initial state of the B-factories at time t, Eq. (2), up to an unphysical global phase that comes from the change of basis, as

$$|i(t)\rangle \;=\; \frac{e^{-\Gamma t}}{\sqrt{2}}\left(|B_\alpha(+\vec{k}),B_{\alpha_\perp}(-\vec{k})\rangle - |B_{\alpha_\perp}(+\vec{k}),B_\alpha(-\vec{k})\rangle\right). \tag{8}$$

This new expression allows us to understand, with help of Eq. (7), that the $B_{\alpha_\perp}$ state is the *father* of the $J/\psi K_S$ decay.

We are now interested to show that, in a good approximation, B_α is the *father* of the $J/\psi K_L$ decay and its branching fraction is equal to that corresponding to the decay $B_{\alpha_\perp} \to J/\psi K_S$. In order to do this, we first obtain, from the measurement of the CP asymmetry in the charged decay ($B^\pm \to J/\psi K^\pm$) [12] by assuming isospin invariance [13], the relation

$$|\langle K^0|T|B^0\rangle| \;\; = \;\; |\langle \bar{K}^0|T|\bar{B}^0\rangle|\,(1+\eta_1), \tag{9}$$

with η_1 being at most of a few percent ($\eta_1 \sim 10^{-2}$). Then, we perform a unitary rotation on the B states in Eq. (9) in order to write this equation in terms of the $\{B_\alpha, B_{\alpha_\perp}\}$ basis, and also a unitary rotation plus a non-unitary perturbation in the K-space, parameterized as $U + \eta_2 A$, with the aim to get Eq. (9) written in the $\{K_S, K_L\}$ basis (here U and A are a unitary and a general 2×2 matrix, respectively, and $\eta_2 \sim 10^{-3}$ is a small parameter that accounts for the CP violation in the neutral Kaon mixing). If we neglect $\eta_{1,2}$ (the $\eta_{1,2} \neq 0$ case is analyzed below) and we use $\langle \bar{K}^0|T|B^0\rangle = \langle K^0|T|\bar{B}^0\rangle = 0$ and Eq. (7), then the following conditions are fulfilled in this new basis

$$\langle K_L|T|B_{\alpha_\perp}\rangle \;\; = \;\; 0 \tag{10}$$

and

$$|\langle K_S|T|B_{\alpha_\perp}\rangle| \;\; = \;\; |\langle K_L|T|B_\alpha\rangle|, \tag{11}$$

as we wanted to show.

The result in Eq. (10) is of great usefulness since, together with Eq. (7), it allows us to reduce to a *single transition* between well defined B-states the following two intensities:

$$I(\ell^-, K_L, \Delta t) \;\; = \;\; c\,|\langle K_L|T|B_\alpha\rangle|^2 |A_{\ell^-}|^2 |\langle B_\alpha|U(\Delta t)|B^0\rangle|^2; \tag{12}$$

$$I(K_S, \ell^+, \Delta t) \;\; = \;\; c\,|\langle K_S|T|B_{\alpha_\perp}\rangle|^2 |A_{\ell^+}|^2 |\langle B^0|U(\Delta t)|B_\alpha\rangle|^2; \tag{13}$$

here $I(X, Y, \Delta t)$ is the probability of having first an X decay and Δt later an Y decay, $\ell^\pm$ refers to flavour specific leptonic decays, $|A_{\ell^\pm}|^2$ is their corresponding branching ratios and 'c' is a common constant factor to both intensities. The notation in Eqs. (12,13) is such that 'K_S' and 'K_L' stand for the final states $J/\psi 2\pi$ and $J/\psi 3\pi$ respectively. Therefore, since we are neglecting CP violation in the Kaon decay, 'K_S' and 'K_L' correspond to definite CP eigenstates with -1 and +1 eigenvalues.

Motivated by the time reversed single B-meson transitions that occur in Eqs. (12) and (13), we propose to measure the following asymmetry,

$$A_T^{exp}(\Delta t) \;\; = \;\; \frac{I(\ell^-, K_L, \Delta t) - I(K_S, \ell^+, \Delta t)}{I(\ell^-, K_L, \Delta t) + I(K_S, \ell^+, \Delta t)}. \tag{14}$$

As it is easily seen using Eq. (11) and assuming $|A_{\ell^+}| = |A_{\ell^-}|$, this asymmetry gets reduced –at this level of approximation– to a direct T-asymmetry in the spirit of Eq. (1),

$$A_T^{exp}|_{\eta_1=\eta_2=0} = A_T(\Delta t) \equiv \frac{|\langle B_\alpha|U(\Delta t)|B^0\rangle|^2 - |\langle B^0|U(\Delta t)|B_\alpha\rangle|^2}{|\langle B_\alpha|U(\Delta t)|B^0\rangle|^2 + |\langle B^0|U(\Delta t)|B_\alpha\rangle|^2}. \tag{15}$$

This observable represents an asymmetry constructed with a well defined transition between physical states and its T-reversed process, therefore it is an observable sensitive to direct T violation.

The case $\eta_{1,2} \neq 0$ is now easily analyzed perturbatively. In fact, if we think of η as a small parameter whose magnitude is at most as large as the maximum between η_1 and η_2, then we have that a term of order η should be added in both RHS of Eqs. (10) and (11). This extra terms end up giving a correction to Eq. (15), which now reads

$$A_T^{exp}(\Delta t) = A_T(\Delta t) + \mathcal{O}(\eta). \tag{16}$$

Therefore, the conclusion is straightforward: *the measurement of*

$$|A_T^{exp}(\Delta t)| \gg \eta \sim 10^{-2} \tag{17}$$

for some Δt, implies direct T violation in the mixing of the B mesons in a model independent way.

As we show in the following Section, the Standard model expectation for A_T is proportional to $\sin(2\beta)$ and hence, as it is shown in Section 4, the inequality in Eq. (17) is experimentally fulfilled.

Notice that besides the T-asymmetry in Eq. (14), it is possible to construct other three T-asymmetries from the different flavour to B_α, $B_{\alpha_\perp}$ transitions. Among these four T-asymmetries there are only two independent, since the others are related to these through a $\Delta t \to -\Delta t$ transformation. Without any conceptual loss, in this work we focus our attention to the A_T^{exp} as defined in Eq. (14).

The approach given along this Section provides an important result since it allows to define in a clear and proper way a direct T-violating asymmetry for this decay beyond any theoretical assumption, including CPT invariance.

3 Interpretation and prediction within the SM

In this Section we make focus on the SM and we analyze the model-independent observable proposed above in this context. This includes the interpretation of the $B_{\alpha,\alpha_\perp}$ states as well as a prediction for the T-violating asymmetry, A_T, in terms of SM parameters. With this purpose, we must first understand the meaning of Eq. (9) within the SM framework.

In order to achieve our goal, we make use of what is known as *CP-tag* [10, 11], therefore we first give a brief review of it. The CP operator is well defined –and conserved– in the free Lagrangian, where, for instance, the Dirac field of the 'a'-particle transforms as

$$\psi_a(\vec{x},t) \xrightarrow{CP} e^{i2\theta_a}\gamma_0 \mathcal{C}\psi_a^{\dagger\,T}(-\vec{x},t); \tag{18}$$

here $\mathcal{C}$ is a unitary 4×4 matrix satisfying the condition $\mathcal{C}\gamma_\mu^*\mathcal{C}^{-1} = -\gamma_\mu$ and θ_a is an undetermined phase. There is one undetermined phase for each particle present, and hence we may say that instead of having *one* CP operator, we have a *family* of them, depending on the choice of these a-priori undetermined phases, which we label generically as CP_Θ (here Θ is a multi-index containing the values of each θ_i).

In this language, if one says that in a given decay there is CP violation, one means that it does not exist any CP_Θ that commutes with the piece of Hamiltonian involved in the decay. Conversely, a decay is said to conserve CP if exists at least one CP_Θ that commutes with the involved Hamiltonian.

For the case of the $SU(2)\times U(1)$ Electroweak Lagrangian of interacting fields, we find that CP-invariance is reached almost everywhere independently of the choice of these undetermined phases, except in the charged-current piece where the mixture of the up and down sectors gives rise to the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix, V_{ij} ($i = u, c, t$ and $j = d, s, b$). It is easily shown that CP-invariance is reached only if it is possible to make a choice of the undetermined phases such that [11]

$$V_{ij}^* = V_{ij}\, e^{2i(\theta_j-\theta_i)}. \tag{19}$$

This condition is not generally satisfied for three generations, as it is the case of the SM.

The main idea of a CP-tag is to observe that, although the whole charged-current piece does not commute with *any* of the CP_Θ, there might be decays for which the piece of Hamiltonian involved in the decay does commute with a specific choice of the phases Θ. This is –within a proper approximation– the case of the $B \to J/\psi K_{S,L}$ decays.

In the Golden Plate decay of the B mesons, $B \to J/\psi K_{S,L}$, assuming that higher order contributions can be neglected, the involved Hamiltonian corresponds to the $W^\pm$-exchanging tree diagram ($B^0 \to J/\psi K^0$ and $\bar{B}^0 \to J/\psi \bar{K}^0$) plus a following Kaon mixing. It is well known that the not-null area of the unitarity triangle of the Kaon system conceives CP violation in the K-mixing, and therefore there is no possible choice of the phases Θ that makes a CP_Θ operator to exactly commute with that piece of Hamiltonian. However, it is mandatory to notice at this point that the Kaon's triangle has the t-side three orders of magnitude smaller that the other two sides, and hence it can be taken to a *flat* form if we approximate $V_{td}V_{ts}^* \approx 0$. (This correspond to a $\mathcal{O}(\lambda^4)$ approximation in the Wolfenstein parameterization [14].) Within this approximation, it is straightforward to obtain the conditions on the phases Θ which determine the CP operator that commutes with the piece of Hamiltonian involved in the decay, namely [11]

$$e^{i(\theta_b-\theta_s)} \equiv \frac{V_{cs}\,V_{cb}^*}{|V_{cs}\,V_{cb}^*|} \qquad e^{i(\theta_s-\theta_d)} \equiv \frac{V_{cd}\,V_{cs}^*}{|V_{cd}\,V_{cs}^*|}. \tag{20}$$

We define the CP_Θ operator from this point forward as the one whose phases accomplish Eq. (20).

With a CP_Θ operator already defined we can now understand what Eq. (9) means within the SM: if we apply the identity operator written as $CP_\Theta^\dagger CP_\Theta$ at both sides of T in the LHS, then we obtain the RHS (with $\eta_1 = 0$). Therefore, Eq. (9) is the experimental verification of our assumption, namely, contributions of higher order than the tree level are not greater than a few percent and, hence, they can be neglected in a first approximation. Therefore, due to the existence of CP_Θ, CP is conserved in this direct decay.

Once the CP_Θ operator is specified we can define its eigenstates,

$$B_{\pm\Theta} = \frac{1}{\sqrt{2}}\left(B^0 \pm CP_\Theta B^0\right), \tag{21}$$

which fulfill the important relationships

$$\langle J/\psi K_S|T|B_{+\Theta}\rangle = 0 \qquad\qquad \langle J/\psi K_L|T|B_{-\Theta}\rangle = 0, \tag{22}$$

due to the commutation of CP_Θ with the Hamiltonian involved in the decay. Notice that if we define $\bar{B}^0 \equiv CP_\Theta B^0$ in Eq. (21) we fix the undetermined phase between B^0 and $\bar{B}^0$. A comparison of Eq. (22) with Eqs. (7) and (10) shows that if there are not significant CP-violating contributions coming from physics beyond the SM in the $B \to J/\psi K$ direct decay then the model independent states of the previous Section could be identified as [3]

$$B_\alpha = B_{+\Theta} \qquad\qquad B_{\alpha\perp} = B_{-\Theta}. \tag{23}$$

Therefore, the direct T-violating observable proposed in the previous Section is, within the SM,

$$A_T(\Delta t) = \frac{\Gamma(B^0 \to B_{+\Theta},\,\Delta t) - \Gamma(B_{+\Theta} \to B^0,\,\Delta t)}{\Gamma(B^0 \to B_{+\Theta},\,\Delta t) + \Gamma(B_{+\Theta} \to B^0,\,\Delta t)}. \tag{24}$$

Once the A_T asymmetry is understood within the SM parameters, it is straightforward to obtain the prediction for it. In fact, the value of this asymmetry within

[3]Observe that this identification would not be valid even in the case of η_1 being equal to zero in Eq. (9) since the presence of not-negligible CP-violating NP contributions, carrying the same strong phase as the SM amplitude, could not be in principle excluded. Therefore, Eq. (9) can not be used in any case as an *a priori* sufficient condition for ensuring in a model independent way the existence of a CP_Θ operator which commutes with the Hamiltonian of the decay.

the SM it has been already computed in Refs. [10, 11] where, in addition, corrections due to the possibility of CPT non-invariance were included. For the purposes of this letter, however, we prefer to obtain the value of A_T in a more straightforward and instructive way assuming CPT invariance. This is easily done if we make a CPT transformation in the second transitions in numerator and denominator of Eq. (24) and observe that the resulting asymmetry is the well known A_{CP} asymmetry, which is predicted within the SM to be proportional to $\sin(2\beta)$,

$$\begin{aligned} A_T(\Delta t) \quad &\xrightarrow{CPT} \quad \frac{\Gamma(B^0 \to B_{+\ominus},\, \Delta t) - \Gamma(\bar{B}^0 \to B_{+\ominus},\, \Delta t)}{\Gamma(B^0 \to B_{+\ominus},\, \Delta t) + \Gamma(\bar{B}^0 \to B_{+\ominus},\, \Delta t)} \\ &= \quad \frac{I(\ell^-, K_L, \Delta t) - I(\ell^+, K_L, \Delta t)}{I(\ell^-, K_L, \Delta t) + I(\ell^+, K_L, \Delta t)} = A_{CP} = \sin(2\beta)\sin(\Delta m \Delta t). \end{aligned} \tag{25}$$

Hence, the SM prediction for the T-asymmetry –assuming CPT invariance– is

$$A_T(\Delta t) = \sin(2\beta)\sin(\Delta m \Delta t). \tag{26}$$

Given the present experimental value for $\sin(2\beta)$ measured through A_{CP} by Babar and Belle, we show in next Section that Eq. (17) is easily fulfilled and direct T violation is positively measured in the B-sector. Moreover, given that the intensities needed to compute A_T are essentially the same that those used to build A_{CP}, we obtain the same high accuracy in the measurement of A_T as the one reached in A_{CP}.

It is worth to notice that the SM prediction in Eq. (26) shows that this T-violating asymmetry, in contrast to the previously measured in the Kaon system [5], is not proportional to the mean life time difference between the physical B states and, therefore, it gets rid of any controversy that might arise due to not negligible $\Delta\Gamma$ [6, 7].

If CPT invariance is assumed in the B-mixing [8], any deviation of A_T^{exp} from the value given by Eq. (26) it is a signal of not-negligible NP CP-violating contributions in the direct $B \to J/\psi K_{S,L}$ decays[4]. In addition, this exploration is independent of any CPT-invariant NP that could be present in the neutral B-mixing.

As it is easily seen, this way of getting the SM prediction for A_T leaves in clear evidence the close connection that exists between A_T and A_{CP} when CPT invariance is assumed. In fact, although the CP violation measured in A_{CP} is due to interference between mixing and decay, the correct choice of the basis in the B-space, $\{B_{+\ominus}, B_{-\ominus}\}$, allows us to see which is the *single transition* that occurs in the mixing of the CP-violating process. Once the transition is isolated, we can understand the A_{CP} asymmetry as an asymmetry between the $B^0 \to B_{+\ominus}$ transition and its CP-conjugated. Given this result, and given that due to the CPT theorem we should expect a signal of T violation that balances this CP violation, it is natural to look

[4]If CPT invariance is not previously assumed, then any deviation from Eq. (26) could be also seen as CPT violation in the mixing.

for it in the asymmetry that is constructed between the $B^0 \to B_{+\Theta}$ transition and its *T-conjugated*. This is the A_T asymmetry proposed in this work (see Eq. (24)).

As an addendum of this Section, it is worth pointing out the difference between this A_T observable here proposed and the usually measured in the B-factories [8],

$$\begin{aligned} \tilde{A}_T \equiv A_{sl} &= \frac{I(\ell^+,\ell^+,\Delta t) - I(\ell^-,\ell^-,\Delta t)}{I(\ell^+,\ell^+,\Delta t) + I(\ell^-,\ell^-,\Delta t)} \\ &= \frac{\Gamma(\bar{B}^0 \to B^0) - \Gamma(B^0 \to \bar{B}^0)}{\Gamma(\bar{B}^0 \to B^0) + \Gamma(B^0 \to \bar{B}^0)}, \end{aligned} \tag{27}$$

which is a T-asymmetry between flavour to flavour transitions. It is straightforward to show that $\tilde{A}_T$ is connected to itself by a CPT transformation of the first terms in numerator and denominator in Eq. (27). Therefore, as it can be easily checked, $\tilde{A}_T$ is also a CP asymmetry, $\tilde{A}_{CP}$. But this $\tilde{A}_{CP}$ asymmetry accounts for CP violation solely in the mixing. Therefore, the usually measured $\tilde{A}_T$ asymmetry is the CPT counterpart of the CP violation in the mixing, whose measurement is still compatible with zero.

We conclude that the T violation expected as a CPT counterpart of the CP violation measured in A_{CP}, should be sought in $B^0 \to B_{+\Theta}$ transitions, and not in $B^0 \to \bar{B}^0$ transitions.

4 Reanalysis of the current experimental data

In this Section we reanalyze the available data of the B-factories and use it to compute the T-violating asymmetry proposed in this work.

The experimental results in References [15] and [16] related to $I(K_S,\ell^+,\Delta t)$ and $I(\ell^-,K_L,\Delta t)$ are obtained through a fit to a formula which assumes $\Delta\Gamma = 0$ (this condition assures that our observable is a direct T-violating observable in the spirit of reference [6]). Since current experiments [8] constrain $\Delta\Gamma/\Gamma < 10^{-3}$, we can safely use this fit: any correction to our results would be at most of this order of magnitude and, hence, it will not modify our conclusion.

The result for the time dependence of the relevant intensities is

$$\begin{aligned} I(\ell^-,K_L,\Delta t) &\propto \frac{e^{-\Gamma\Delta t}}{4\Gamma} \times \begin{cases} (1 + (0.716 \pm 0.080)\sin(\Delta m \Delta t)) & \text{Babar [15]} \\ (1 + (0.641 \pm 0.057)\sin(\Delta m \Delta t)) & \text{Belle [16]} \end{cases} \\ I(K_S,\ell^+,\Delta t) &\propto \frac{e^{-\Gamma\Delta t}}{4\Gamma} \times \begin{cases} (1 - (0.691 \pm 0.040)\sin(\Delta m \Delta t)) & \text{Babar [15, 17]} \\ (1 - (0.643 \pm 0.038)\sin(\Delta m \Delta t)) & \text{Belle [16]} \end{cases} \end{aligned}$$

and therefore, using Eq. (14), we obtain the result for the direct T-violating observable,

$$A_T^{exp}(\Delta t) = \begin{cases} (0.703 \pm 0.044)\sin(\Delta m \Delta t) & \text{Babar} \\ (0.642 \pm 0.034)\sin(\Delta m \Delta t) & \text{Belle} \end{cases} \tag{28}$$

As it is easily seen, Eq. (28) easily satisfies the requirement in Eq. (17). Therefore, we can positively assert that a reinterpretation and a reanalysis of the B-factories available data have provided us the evidence of direct T violation in the B system. As far as we are concerned, this is the first evidence in the violation of this symmetry in this sector, and also the second evidence of T violation after the CPLEAR experiment.

The analysis of Eq. (28) shows that $A_T^{exp}(\Delta t) = \sin(2\beta)\sin(\Delta m \Delta t)$ within the experimental error. In fact, since no direct CP violation has been measured in the $B^0 \to J/\psi K_{S,L}$ decays through this data, then this equality should hold (c.f. Eq. (26)). Moreover, in this case of no direct CP violation the two independent T-asymmetries mentioned in Section 2 are connected by CPT and get reduced to the same, Eq. (28).

It is worth stressing at this point the subtlety in the evidence of direct T violation presented in Eq. (28). Although we have used the available data that the B-factories use to construct the CP-asymmetries, we have recombined them in such a way that, as explained in Section 2, they end up building an asymmetry which is a direct test of T violation in a model independent way.

5 Conclusions

We have reanalyzed the observables measured by the B-factories and we have shown that they imply direct T violation in the B system.

To achieve this conclusion we have proposed an asymmetry which, in a model independent way and without assuming CPT invariance, consists in the comparison of the transition between a flavour B-state and a B_α-state, and its T-reversed: $\Gamma(B^0 \to B_\alpha, \Delta t)$ versus $\Gamma(B_\alpha \to B^0, \Delta t)$. We have shown how the precise definition of the B_α-state arises from the concept of tagging, which filters the information of a given decay into the structure of the tagged meson. The argument in this letter states that if the measurement of the proposed T-asymmetry, $A_T^{exp}(\Delta t)$ (Eq. (14)), is greater than the quoted $\eta \sim 10^{-2}$ for some Δt then there is a signal of direct T violation. The reanalysis of the available experimental data fully overshoots this condition by more than ten standard deviations (Eq. (28)) and hence it provides clear evidence of direct T violation in the B system.

The experimental result for the T-asymmetry is consistent with the Standard Model prediction, $A_T^{exp}(\Delta t) = \sin(2\beta)\sin(\Delta m \Delta t)$. Moreover, the Standard Model analysis has shown that this observable does not require a non negligible mean life time difference ($\Delta\Gamma$) between the physical neutral B mesons and, in addition, that it represents the T violation expected from the CP-asymmetry $A_{CP}(B \to J/\psi K_{S,L})$ due to the CPT theorem.

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